

## LOWER LIMIT ON THE STRENGTH AND FILLING FACTOR OF EXTRAGALACTIC MAGNETIC FIELDS

K. DOLAG<sup>1</sup>, M. KACHELRIESS<sup>2</sup>, S. OSTAPCHENKO<sup>2,3</sup>, R. TOMÀS<sup>4</sup><sup>1</sup>Max-Planck-Institut für Astrophysik, Garching, Germany<sup>2</sup>Institutt for fysikk, NTNU, Trondheim, Norway<sup>3</sup>D. V. Skobeltsyn Institute of Nuclear Physics, Moscow State University, Russia<sup>4</sup>II. Institut für theoretische Physik, Universität Hamburg, Germany*Draft version October 29, 2010*

## ABSTRACT

High energy photons from blazars can initiate electromagnetic pair cascades interacting with the extragalactic photon background. The charged component of such cascades is deflected and delayed by extragalactic magnetic fields (EGMF), reducing thereby the observed point-like flux and leading potentially to multi degree images in the GeV energy range. We calculate the fluence of 1ES 0229+200 as seen by Fermi-LAT for different EGMF profiles using a Monte Carlo simulation for the cascade development. The non-observation of 1ES 0229+200 by Fermi-LAT suggests that the EGMF fills at least 60% of space with fields stronger than  $\mathcal{O}(10^{-16} - 10^{-15})$  G for life times of TeV activity of  $\mathcal{O}(10^2 - 10^4)$  yr. Thus the (non-) observation of GeV extensions around TeV blazars probes the EGMF in voids and puts strong constraints on the origin of EGMFs: Either EGMFs were generated in a space filling manner (e.g. primordially) or EGMFs produced locally (e.g. by galaxies) have to be efficiently transported to fill a significant volume fraction, as e.g. by galactic outflows.

*Subject headings:* magnetic fields: origin – magnetic fields: extragalactic – gamma rays: galaxies – galaxies: active

## 1. INTRODUCTION

While magnetic fields are known to play a prominent role for the dynamics and in the energy budget of astrophysical systems on galactic and smaller scales, their role on larger scales is still elusive (Widrow 2002; Kulsrud & Zweibel 2008). Extragalactic magnetic fields (EGMF) are notoriously difficult to measure and the data are incomplete. So far only in a few galaxy clusters observational constraints have been obtained, either by observing their synchrotron radiation halos or by performing Faraday rotation measurements (RMs). Within galaxy clusters the inferred magnetic fields are between 0.1 and 1.0  $\mu$ G on scales as large as 1 Mpc, and can be as strong as 30  $\mu$ G localized inside cluster cool cores. However, as both observational methods need a prerequisite to measure magnetic fields (high thermal density for RMs and presence of relativistic particles for radio emission), they have been successfully applied only to high density regions of collapsed objects as galaxies and galaxy clusters. Fields significantly below  $\mu$ G level are barely detectable with these methods. Also other constraints, for instance the absence of distortions in the spectrum and the polarization properties of the cosmic microwave background radiation implies only a fairly large, global upper limit on the EGMF at the level of  $10^{-9}$  G.

The observed magnetic fields in galaxies and galaxy clusters are assumed to result from the amplification of much weaker seed fields. Such seeds could be created in the early universe, e.g. during phase transitions, and then amplified by plasma processes. Alternatively, an early population of starburst galaxies or AGN could have generated the seeds of the EGMFs at redshift between five and six, before galaxy clusters formed as gravitationally bound systems. In both cases, a large fraction of the material collapsing to today's visible structures will be seeded by such fields, but whether a significant

fraction of the volume of the universe can be filled by such EGMFs depends on the efficiency of the transport processes involved. A quite different possibility is that the ejecta of AGN magnetized the intracluster medium only at low redshifts, and that thus the EGMF are confined within galaxy clusters and groups. The detection of EGMFs outside clusters is therefore crucial in discriminating different models for the origin of their seed fields.

An alternative approach to obtain information about the EGMFs is to use its effect on the radiation from TeV gamma-ray sources. The multi-TeV  $\gamma$ -ray flux from distant blazars is strongly attenuated by pair production on the infrared/optical extragalactic background light (EBL), initiating electromagnetic cascades in the intergalactic space. The charged component of these cascades is deflected by the EGMF. Potentially observable effects of such electromagnetic cascades in the EGMF include the delayed “echoes” of multi-TeV  $\gamma$ -ray flares or gamma-ray bursts (Plaga 1995; Murase et al. 2008) and the appearance of extended emission around initially point-like  $\gamma$ -ray sources (Aharonian et al. 1994; Neronov & Semikoz 2007; Dolag et al. 2009; Elyiv et al. 2009; Neronov et al. 2010a).

An additional way to derive lower limits on the EGMF has been pointed out recently by Neronov & Vovk (2010) and Tavecchio et al. (2010a): Since the deflection of the cascade flux into an extended halo weakens the point-like image, the non-observation of TeV blazars in the GeV range by Fermi-LAT can be used to derive a lower limit on the EGMF. Particular suitable candidates are blazars with a very hard TeV spectrum like 1ES 0229+200 that show a low intrinsic GeV emission. In this way, Neronov & Vovk (2010) and Tavecchio et al. (2010a) derived the lower bound  $B \gtrsim 5 \times 10^{-15}$  G on the EGMF. Note that Ando & Kusenko (2010) found evidence for gamma-ray halos in the stacked images of

the 170 brightest active galactic nuclei observed with Fermi-LAT. The size of these halos are consistent with  $B \sim 10^{-15}$  G, however it is unclear if the excess found is real or due to the imperfect knowledge of the Fermi-LAT point spread function (PSF) as argued by Neronov et al. (2010b). All these analyses assumed a stationary source and did not discuss the effect of time delays induced by EGMFs.

In this work, we will concentrate on 1ES 0229+200 and follow essentially the same assumptions about the source and the sensitivity of Fermi-LAT as Tavecchio et al. (2010a). We will improve on previous analyses in two respects: First, we use a Monte Carlo simulation for the development of electromagnetic cascades in the EBL that includes the effects of magnetic fields like synchrotron radiation and deflections of electrons. Moreover, we calculate the time delay that is induced by the EGMF deflections. Second, we examine the influence of a more realistic, structured magnetic field on the EGMF limit.

## 2. SIMULATION PROCEDURE

We inject at the redshift  $z = 0.14$  photons with an energy distribution given by  $\mathcal{F} \propto E^{-2/3}$  and a maximal energy  $E_{\max} = 20$  TeV. Such a hard injection spectrum gives a reasonable fit to the HESS data and is consistent with recent SWIFT (Burrows et al. 2004) observations as argued by Tavecchio et al. (2009). We assume also a relatively low Lorentz factor,  $\Gamma = 10$ , i.e.  $\Theta_{\text{jet}} = 6^\circ$ , in order to derive a conservative lower bound on the EGMF.

We follow electromagnetic cascades initiated by these high energy photons with the Monte Carlo code introduced by Kachelrieß et al. (2009). Since Fermi-LAT provides only an upper limit on the photon flux from 1ES 0229+200 it is sufficient to assume a radial-symmetric halo and to calculate the deflections and time delays as described in (Dolag et al. 2009). We use as EBL background the best-fit model from the calculations of Kneiske & Dole (2010).

We divide the photons arriving at the observer into a point-like flux and a halo outside a circle with angle  $\vartheta_*$  around the source. For Fermi-LAT, we use for  $\vartheta_*$  an analytical approximation of the angle  $\vartheta_{95}$  containing 95% of the flux emitted by a point-source given by  $\vartheta_{95} \approx 1.68^\circ (E/\text{GeV})^{-0.77} + 0.2^\circ \exp(-10 \text{ GeV}/E)$ . Above 300 GeV,  $\vartheta_{95}$  is set equal to  $0.11^\circ$ , a value typical for the resolution of atmospheric Cherenkov telescopes.

## 3. RESULTS FOR DIFFERENT EGMF MODELS

In Figs. 1 and 2 we show our results for the fluence contained inside the 95% confidence contour of the PSF of Fermi-LAT. Additionally, these figures contain the HESS observations (Aharonian et al. 2007) as black dots with error bars and the Fermi-LAT upper limits derived by Tavecchio et al. (2010a). The fluences have been normalized fitting them to the HESS data.

In Fig. 1, we have used a uniform magnetic field so that our results can be directly compared with the analytical estimates of Tavecchio et al. (2010a). Note that a turbulent field with correlation length  $L_{\text{cr}}$  much larger than the mean free path  $l_{\text{IC}}$  of electrons in the Thomson regime,  $L_{\text{cr}} \gg l_{\text{IC}} \sim 1$  kpc, is well approximated by a uniform field. For smaller correlation lengths,  $L_{\text{cr}} \ll l_{\text{IC}}$ , the electron diffuses in the small-angle deflection regime, requiring larger magnetic fields for the same deflection

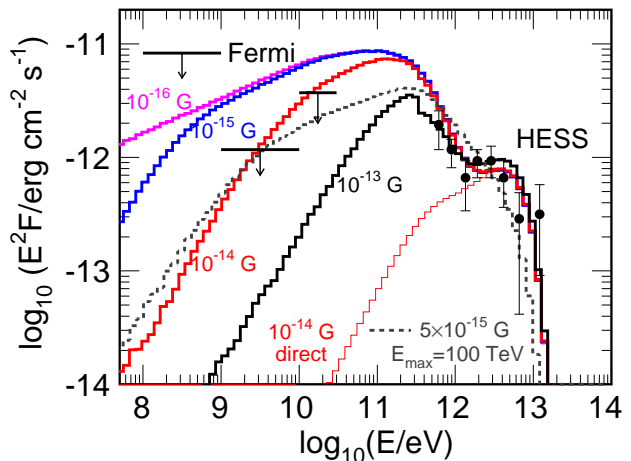


FIG. 1.— Fluence contained inside the 95% confidence contour of the PSF of Fermi-LAT as function of energy together with Fermi-LAT upper limits and HESS observations for a uniform EGMF with strengths varying from  $B = 10^{-16}$  G to  $B = 10^{-13}$  G with  $E_{\max} = 20$  TeV (solid) and 100 TeV (dashed). The direct component for  $B = 10^{-14}$  G is also shown.

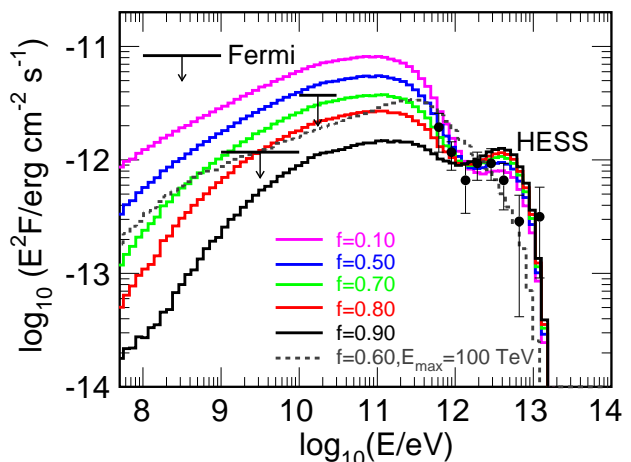


FIG. 2.— Fluence contained inside the 95% confidence contour of the PSF of Fermi-LAT as function of energy for a EGMF with top-hat profile and filling factor  $f$  varying from  $f = 0.1$  to  $f = 0.9$  with  $E_{\max} = 20$  TeV (solid) and 100 TeV (dashed).

angle. Demanding that the cascade flux is below the upper limits of Fermi-LAT leads to a lower limit on the magnetic field strength of  $\sim 10^{-14}$  G. For this case the direct component, i.e. photons arriving at the detector without cascading, is also shown. Note that for small  $E_{\max}$  the transition from the direct to the cascade contribution leads to a break at  $\sim$  TeV in the spectrum, as suggested by the HESS data.

While our limit agrees reasonably well with the analytical estimate of Tavecchio et al. (2009), the shape of the cascade flux obtained differs. There are several reasons responsible for these differences: First, Tavecchio et al. (2009) assume that the spectral shape of the cascade flux below the threshold energy  $\sim 10^{11}$  eV is given by  $\mathcal{F} \propto E^{-0.5}$  for negligible magnetic fields. Such a slope typical for the regime of Thomson cooling is however restricted to energies  $E \lesssim 10^8$  eV, while at higher energies a plateau  $\mathcal{F} \propto E^\alpha$  with  $\alpha \sim -0.9$  is ex-

pected (Berezinsky et al. 2010). Second, deflections in the EGMF lead even for isotropic emission to extended images of point-like sources. This effect has been neglected in Tavecchio et al. (2009). Third, using full probability distributions for the interactions there is a non-negligible probability for photons not to interact, especially towards the low-energy end of the injected energy range. Finally, the energy dependent PSF of Fermi introduces an artificial energy dependence of the point-like flux  $\mathcal{F} \propto \vartheta_{95}^2$ . Note that an increase in  $E_{\max}$  from 20 to 100 TeV *reduces* the limit on the magnetic field strength to  $\sim 5 \times 10^{-15}$  G, see Fig. 1, while a further increase of  $E_{\max}$  strengthens the limit again. The counter-intuitive behavior between 20 to 100 TeV is caused by the dominance of direct photons at the high-energy part of the spectrum for small  $E_{\max}$ .

We discuss next the consequence of time delays induced by the EGMF. We stress that the non-observation of 1ES 0229+200 by Fermi-LAT is a signature for non-zero EGMFs, even if the delay of the Fermi signal would exceed the life time  $\tau$  of 1ES 0229+200 as TeV source. However, the numerical value of the limit deduced using deflections would be modified. For  $B = 5 \times 10^{-15}$  G, we find as average time delay  $1 \times 10^6$ ,  $1 \times 10^5$ , and 5000 yr for the three energy bins (0.1–10), (1–10), and (10–30) GeV. Thus the high-energy bin of the Fermi data can be used to derive the constraint as above, if 1ES 0229+200 is a relatively stable source over a time scale longer than  $10^4$  yr. Even if  $\tau$  is much smaller, say around 100 yr, the lower limit on  $B$  weakens only by a factor 10 to  $B = \mathcal{O}(10^{-16}$  G).

Since the EGMF is strongly structured, one may wonder how a non-uniform field modifies this limit. In particular, we want to address the question whether the presence of relatively strong fields concentrated inside cosmic structures like filaments could mimic the effect of an EGMF present also in voids. As simplest possible test, we use first a top-hat profile for the structure of the EGMF: We set the field strength to zero in a fraction  $1-f$  of space and use a value which in general is assumed to be representative for filaments,  $B = 10^{-10}$  G, in the remaining part. For the separation of the peaks we use  $D = 10$  Mpc motivated by the typical distances between cosmological structures, although the exact value of  $D$  plays no role as long as  $(1-f)D \ll l_\gamma$ , with  $l_\gamma$  as mean free path of photons. The dependence of the fluence contained inside the PSF of Fermi-LAT on the filling factor  $f$  is shown in Fig. 2. To be consistent with the Fermi upper limits, sufficiently strong magnetic fields should fill  $\gtrsim 80\%$  of space. The derived limit on the filling factor is practically independent of the source life time  $\tau$  and  $B$ , as long as the field is stronger than  $\gtrsim 5 \times 10^{-15}$  G. As in the previous case, by assuming a higher injected  $E_{\max}$  the required filling factor is slightly reduced to 60%.

The failure of strong fields filling only a small fraction of the universe to suppress sufficiently the point-like cascade flux can be understood as follows: The HESS observations of 1ES 0229+200 cover the energy range 0.5–11 TeV. In the same energy range, the mean free path  $l_\gamma$  of VHE  $\gamma$ -rays through the EBL varies between 1000 and 50 Mpc and is thus always much larger than the typical extension of regions with large fields,  $(1-f)D$ . For the energies considered, the cascade consists typically of only three steps,  $\gamma \rightarrow e^\pm \rightarrow \gamma$ . Since the mean free path

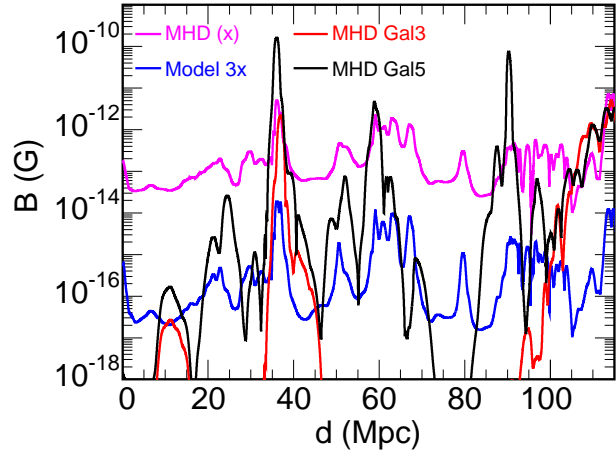


FIG. 3.— The EGMF component perpendicular to the line-of-sight towards 1ES 0229+200 from four different MHD simulations.

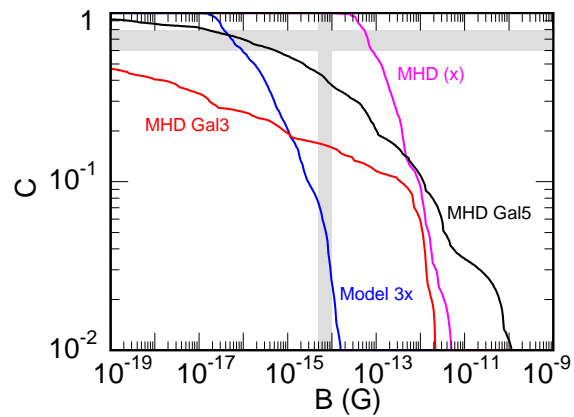


FIG. 4.— Cumulative volume filling factor  $C(B)$  for the four different EGMF models found in MHD simulations.

$l_{IC}$  of electrons in the Thomson regime is very small,  $l_{IC} \sim 1$  kpc, all cascades with electrons created outside the strong-field regions are undeflected. Thus it is not possible to trade smaller values of  $f$  against larger values of  $B$ : Increasing the field strength beyond  $\sim 10^{-13}$  G leads only to an increase of the deflection, while the fraction of cascades deflected outside the Fermi PSF remains constant.

To mimic the even more complex situation in presence of cosmological structures, we have used magnetic fields derived from several cosmological MHD simulations using constrained initial conditions (Dolag et al. 2004, Donnert et al. 2009; for alternative simulations see e.g. Ryu et al. 2008). Therefore they reproduce fairly well the true large scale matter distribution, out to a distance of  $\approx 114$  Mpc, cf. for more details Dolag et al. (2005). We extracted the EGMF as predicted by these simulations along the line of sight towards the position of 1ES 0229+200 for several models for the magnetic seed field. A comparison of the EGMF component perpendicular to the line-of-sight towards 1ES 0229+200 obtained in the models is shown in Fig. 3.

Most magnetic seed models used in cosmological simulations assumed a space filling (e.g. primordial) magnetic seed field of order  $10^{-12}$  G, which inside galaxy clusters is



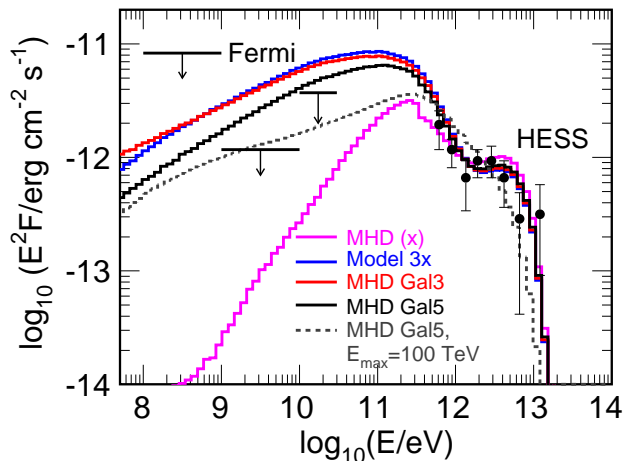


FIG. 5.— Fluence contained inside the 95% confidence contour of the PSF of Fermi-LAT as function of energy for EGMFs from four different MHD simulations with  $E_{\max} = 20$  TeV (solid) and 100 TeV (dashed).

amplified by the collapse and additionally by shear turbulence up to the observed  $\mu\text{G}$  level. For the purpose of this work we have selected the available simulation with the lowest primordial seed field of  $10^{-13}$  G (MHDx), which inside voids is even diluted to values of order of  $10^{-14}$  G due to cosmic expansion. To construct a second model with magnetic fields as low as  $10^{-17}$  G inside voids, we scaled down the magnetic field of the original simulation by a factor proportional to the local density to the power  $2/3$  (Model 3x) with the fix point at the core density of galaxy clusters. Thereby, the Faraday RMs of the newly constructed model within galaxy clusters does not significantly change, whereas the magnetic field in filaments and voids drop by nearly three orders of magnitude compared to the original simulation.

Models which intrinsically produce lower magnetic fields (and filling factors) in filaments and voids are those where the seed field originates from the galaxies formed. In such simulations, galaxies are identified at early times, and their halos are magnetized according to the magnetic field observed in nearby galaxies. So far such simulations do not include any transport processes for the magnetic field (like galactic outflows or AGN activity) beyond the large scale potential well in which galaxies live. Nevertheless, these models reproduce well the observed magnetic field properties within galaxy clusters, since the gas component of the galactic halos is stripped during the formation process of the cluster and the magnetic field gets well mixed and subsequently amplified by the turbulence within the intercluster medium. The result of such a simulation is the model (MHD Gal3) from Donnert et al. 2009. As galaxies in filaments form later than their counterparts in high density environment, we have also extracted the magnetic field from a model which subsequently put magnetic fields into newly formed halos also at lower redshift (MHD Gal5). The main difference to the previous model is the presence of more magnetized structures within filaments whereas the magnetic field properties in galaxy clusters do not change significantly.

The simulation used covers only up to distances of 114 Mpc, and therefore we are forced to extend the magnetic field profile beyond that point. For this purpose we

assume that the extended field has the same statistical properties as the simulated patch. In practice, we simply mirror and repeat the field beyond the first 114 Mpc. In Fig. 4 we show the cumulative volume filling factor, i.e. the fraction  $C(B)$  of volume occupied by regions with field strength  $> B$ . The vertical and horizontal bands stand for the minimum magnetic field and filling factor, respectively, required to avoid the Fermi limit, as obtained in Figs. 1 and 2.

The fluence contained inside the PSF of Fermi-LAT for the EGMF models MHDx, MHD Gal3 and MHD Gal5 is shown in Fig. 5. From the results for the top-hat model, we anticipate that the EGMF in the models MHD3x and MHD Gal3 is too weak and does not lead to a significant modification of the fluence, see Fig. 4: Since the model MHD Gal5 is not far from the intersection of the two bands, we expect it not to lie far from the Fermi limit. In Fig. 5 it is seen how in the particular case of  $E_{\max} = 100$  TeV this model is marginally consistent with the Fermi-LAT observations.

Finally, the fluence is several orders of magnitude below the observational limits for fields as strong as in the model MHDx. In such a case, extended images in the GeV range as predicted e.g. by Neronov et al. (2010a) will be impossible to observe with Fermi-LAT.

We would like to point out, that on the other hand, all these models are in agreement with observations of magnetic fields in galaxy clusters – which so far is the only place where the strength and structure of magnetic fields has been directly detected – and therefore demonstrate the constraining power of using high energy photons to infer the origin and the processes leading to EGMFs.

#### 4. SUMMARY

We have calculated the fluence of 1ES 0229+200 as seen by Fermi-LAT using a Monte Carlo simulation for the cascade development. We have discussed the effect of different EGMF profiles on the resulting suppression of the point-like flux seen by Fermi-LAT. Since the electron cooling length is much smaller than the mean free path of the TeV photons, a sufficient suppression of the point-like flux requires that the EGMF fills a large fraction along the line-of-sight towards 1ES 0229+200,  $f \gtrsim 0.6$ . The lower limit on the magnetic field strength in this volume is  $B \sim \mathcal{O}(10^{-15})$  G, assuming 1ES 0229+200 is stable at least for  $10^4$  yr, weakening by a factor of 10 for  $\tau = 10^2$  yr. These limits put very stringent constraints on the origin of EGMFs: Either the seeds for EGMFs have to be produced by a volume filling process (e.g. primordial) or very efficient transport processes have to be present which redistribute magnetic fields that were generated locally (e.g. in galaxies) into filaments and voids with a significant volume filling factor.

*Acknowledgments.* We are grateful to L. Costamante and D. Paneque for discussions and to the referee for his/her useful remarks. K.D. is supported partly by the DFG SFB 1177 and a Cluster of Excellence, while S.O. acknowledges a fellowship from the program Romforskning of Norsk Forskningsradet.

*Note added.* After the completion of this work the preprint of Tavecchio et al. (2010b) appeared in which these authors study the four BL Lac objects (RGB J0152+017, 1ES 0229+200, 1ES 0347-121 and PKS 0548-

322) and derive a bound of  $B \sim 5 \times 10^{-15}$  G on a space filling magnetic field.

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